Bluetooth Tutorial

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Overview

- Introduction
- Software/Interface Stack
- Device Description
  - Radio Specification
  - Baseband Specification
  - Link Management and Control
- Service Discovery
- Emulation/Telephony Protocols
- Integration with other wireless services
- Available hardware

Introduction

- Named after a medieval Danish king
- Intended as a replacement for short-range cables
  - Inexpensive
  - Flexible
  - Robust

Bluetooth SIG

- Over 1500 companies
  - Started by Ericsson, Nokia, IBM, Intel, and Toshiba
- Assembled specifications
  - Functional descriptions
  - Leaves several implementation details open to the developer

Market Estimates

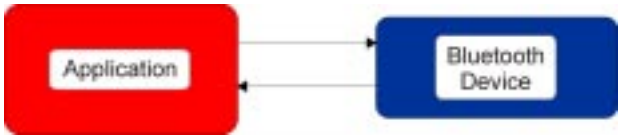
- Number of units expected to reach 260 Million by 2003
- Worldwide sales market expected to exceed $3 Billion by 2005
  - Market figure for devices only
  - Does not include applications

General Market Goal

- Single-chip solution
  - Around $5 per device
- Risks of current marketing
  - Success of devices a function of
    - Engineering/Manufacturing
    - Marketing
  - Danger of hype over-selling technology

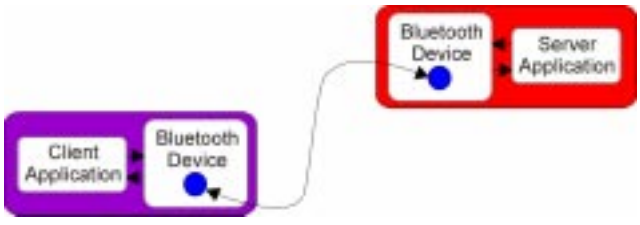
Device Usage

- (almost) Stand-alone wireless connection
  - Needs external application to drive services

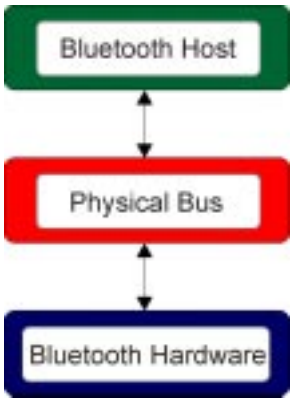


Device Communications

- Client/Server (Master/Slave) configuration
  - Devices are inherently equal
  - Application determines identity



Software/Interface Stack



- Bluetooth Host
  - Host Controller Interface driver
  - Physical Bus driver
- Physical Bus
  - Physical Bus Firmware
- Bluetooth Hardware
  - Host Controller Interface firmware
  - Baseband controller

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Connecting to Device

- Host Controller Interface
  - Allows control interaction with Bluetooth hardware
- Transport layer
  - Physical connection between host and Bluetooth hardware

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Host Controller Interface

- Uniform interface to access Bluetooth hardware capabilities
- Contains sets of commands for hardware
- Contains handle to possible events
- Contains access to error codes

Transport Layer

- Transport layer between host controller driver and host controller
- Intended to be transparent
  - Host controller does not care whether it is running over USB or PC card
  - Allows upgrade of HCI without affecting transport layer

Transport Options

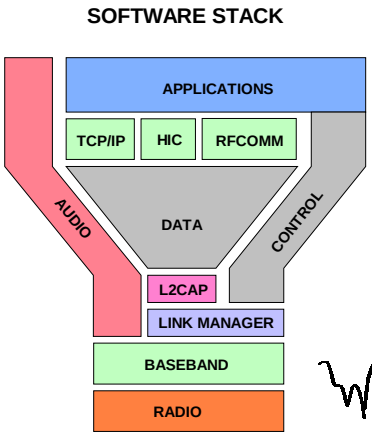
- Standard describes three basic transport formats
  - USB Transport
    - Universal Serial Bus
  - RS232 Transport
  - UART Transport
    - Universal Asynchronous Receiver/Transmitter
    - Serial interface
      - Can be set to RS232 settings

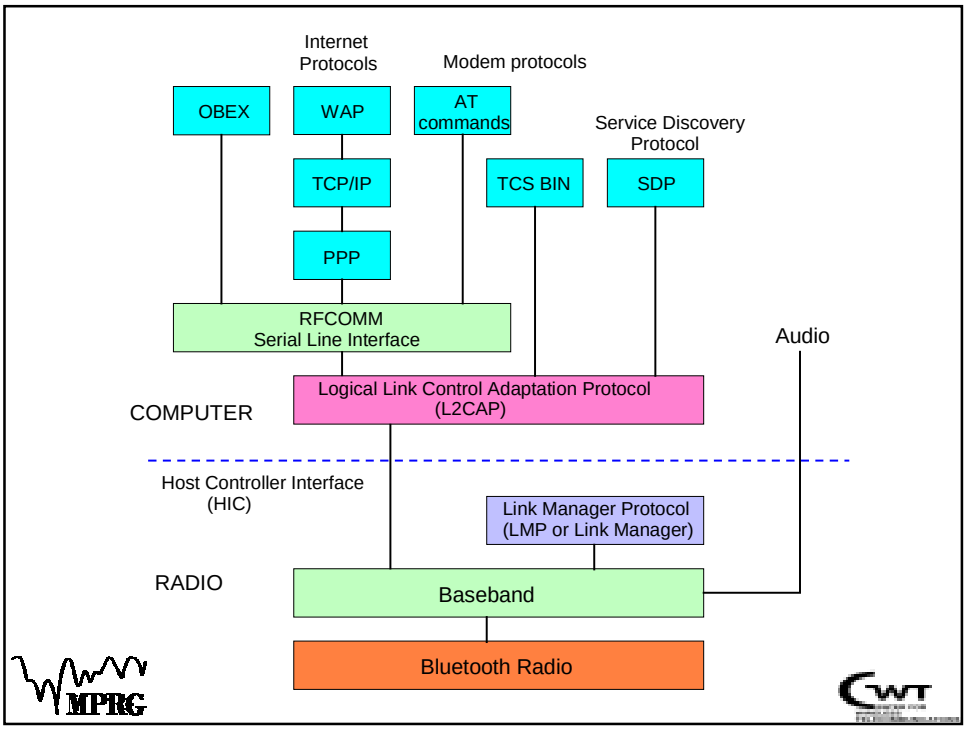
Current Point in Presentation

- Reviewed basic device usage
  - Interfacing to the “outside world”
- Next sections cover
  - RF and baseband description
  - Link management
  - Services
  - Device/kit availability

Bluetooth is more than a radio

- **Forms ad hoc networks**
  - Piconet: up to 7 devices can be actively connected to a master station
  - Additional devices can be connected in a parked or hold mode
  - Piconets can form Scatter Nets for almost unlimited connectivity
- **Software Stack**





Bluetooth Networking

- **Piconet formed by up to seven active Bluetooth devices**
  - Master/Slave configuration
  - Additional slaves can be placed in a “parked” state
    Devices are not active but remain synchronized
  - Connection, synchronization, parked/active controlled by master
  - All devices connected in a piconet share timing and frequencies
- **Scatternet formed by two or more Piconets**
  - One master per piconet but a master in one piconet can participate as a slave in a different piconet
  - Slaves are time division multiplexed into more than one piconet
  - Piconets not time or frequency synchronized

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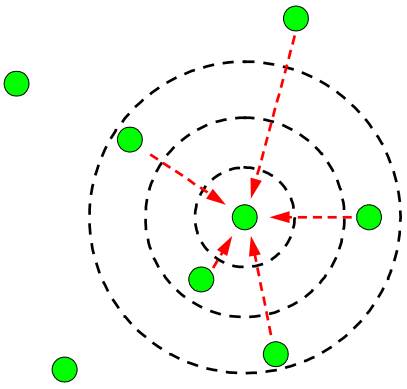
Establishing a connection

Bluetooth units transmit inquiry message to find other Bluetooth units



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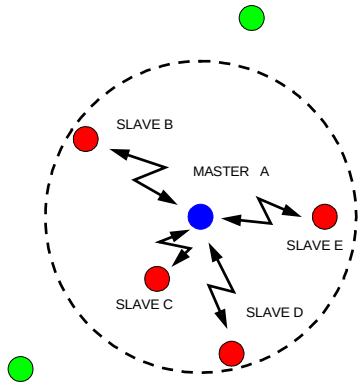
Master/Slave Piconet

- One unit becomes the master and the others slaves
- Master/slave relationship establishes timing
- A slave can become a master in another Piconet. This connects two Piconets into a Scatter Net



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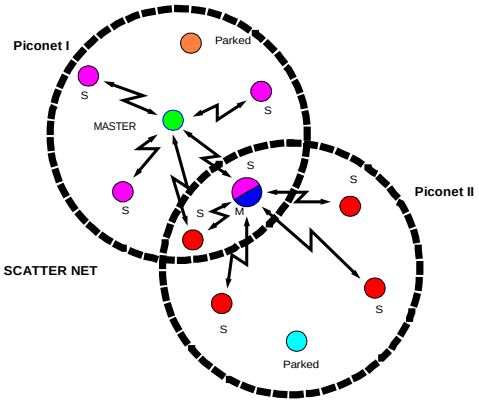
Bluetooth Pico and Scatter Nets



- Master in one piconet can be a slave in another
- Addressing limits number of active devices in a piconet to 7
- An indefinite number of parked devices remain synchronized with the piconet but are not active

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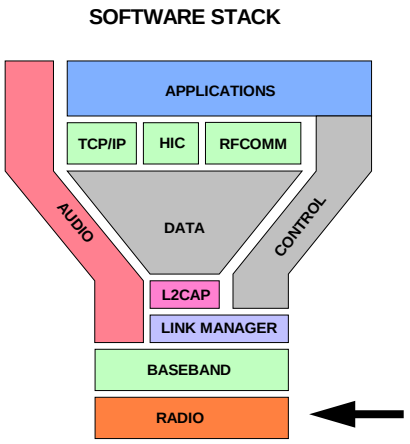
Bluetooth Radio



Bluetooth Radio

- **Radio specification**
  Goal is a single chip radio
  Relaxed RF specifications reduce cost
- **Operation under unlicensed international rules**
  US: FCC Part 15
  Europe: ESTI 300-328
- **2.4 GHz ISM band radio**
  Frequency Hop (FH) spread spectrum: 1600 hops/sec
  Time Domain Duplex (TDD)

Bluetooth Radio

Bluetooth is a 2.4 GHz ISM band spread spectrum radio

- 2400 - 2483.5 MHz allows world wide (almost) operation
- 1600 hops/sec (625 µsec) frequency hopper
- 79 One MHz channels (23 in France, Japan)
- Time Division Duplex
- Tx power 0 dBm to 20 dBm
- Range 10 cm to 10 m at low power (0dBm)
- Data rates: from 108/108 kbps symmetric channel to 723/57 kbps asymmetric channel
- Isosynchronous (circuit switched) or asynchronous (packet)

Bluetooth International Allocations

Geography	Regulatory Allocation	Blue Tooth Channels
USA	2.400 – 2.4835 GHz	f = 2402 + k MHz k = 0…78
Europe	2.400 – 2.4835 GHz	f = 2402 + k MHz k = 0…78
Spain	2.445 – 2.475 GHz	f = 2449 + k MHz k = 0…22
France	2.4465 – 2.4835 GHz	f = 2454 + k MHz k = 0…22
Japan	2.471 – 2.497 GHz	f = 2473 + k MHz k = 0…22

- FCC Part 15 in the US
- ETSI 300-328 in the European Union, Africa, and Eastern Europe
- Harmonization efforts currently under way

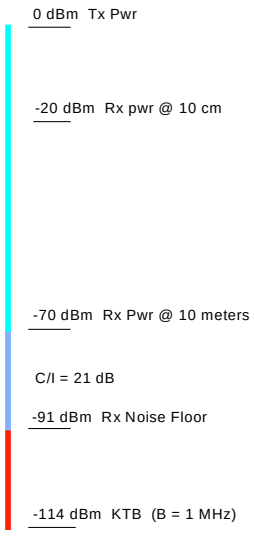
BT Power Levels

Power Class	Maximum Power	Nominal Power	Minimum Power (at Max Pwr setting)	Power Control
1	100 mW (20 dBm)	N/A	0 dBm	4 dBm – 20 dBm -30 dBm - 0 dBm (optional)
2	2.5 mW (4 dBm)	0 dBm	0.25 mW (-6 dBm)	-30 dBm - 0 dBm (optional)
3	1 mW (0 dBm)	N/A	N/A	-30 dBm - 0 dBm (optional)

Power control required for high powered Bluetooth devices to minimize interference

Power control requires receiver RSSI function

BT Link Budget



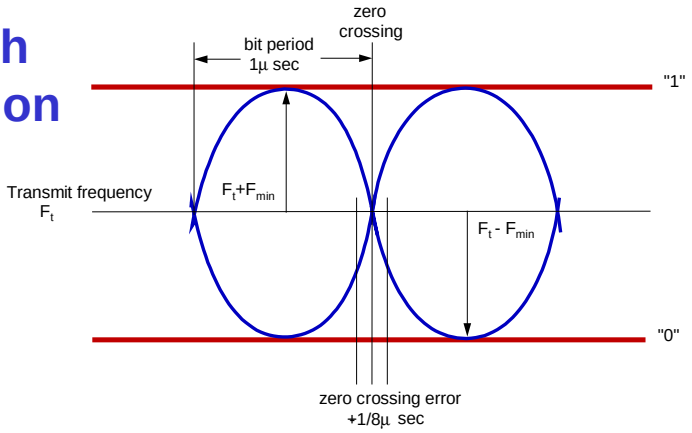
TX power of 0 dBm

C/I = 21 dB

NF = 23 dB

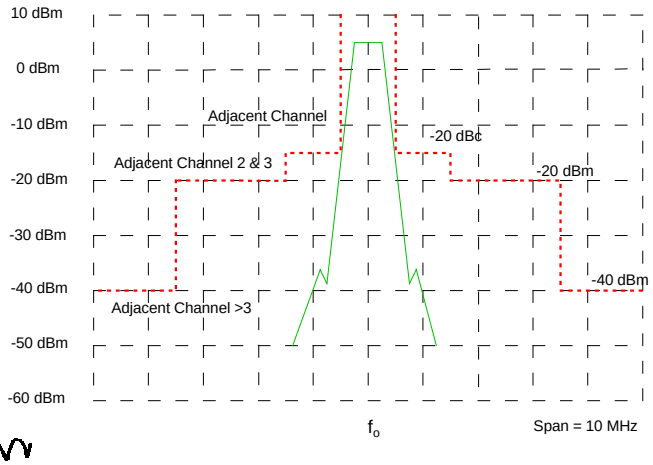
Results in a radio with very relaxed specifications

Bluetooth Modulation

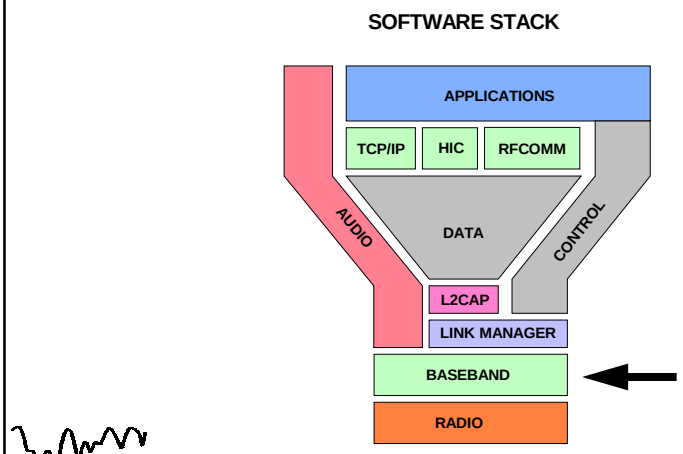


- Modulation: Gaussian filtered FSK (GFSK) BT=0.5
- Modulation Index: 0.28 - 0.35
- Deviation: Fmin > 115 KHz
- Ft - Fmin = “0” Ft + Fmin = “1”
- Symbol Timing: 20 ppm

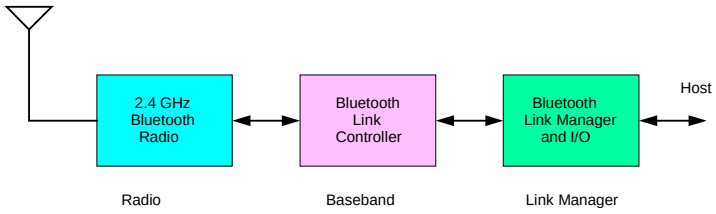
Bluetooth Spectrum Mask



Bluetooth Baseband



Baseband Controller



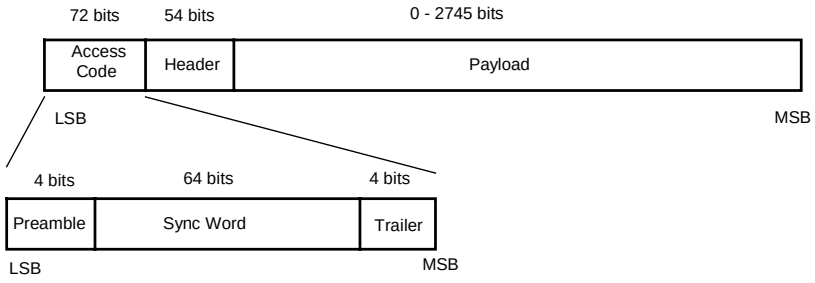
- **Baseband:** baseband protocols and low level link routines
- **Link Manager:** Link Layer messages for setup and link control

Bluetooth Baseband

- **Frequency Hop Time Division Duplex Channel**
  Channel based on a 625 μsec time slot (1600 hop/sec)
  220 μsec of the slot lost to PLL settling

- **Bluetooth uses both circuit and packet switched channels, supports:**
  - Up to 3 simultaneous 64 kbps synchronous voice channels
  - Simultaneous synchronous voice and asynchronous data channel
  - Asynchronous data channel: 721/57.6 kbps asymmetric
    432.6 kbps symmetric

Bluetooth Packet Format



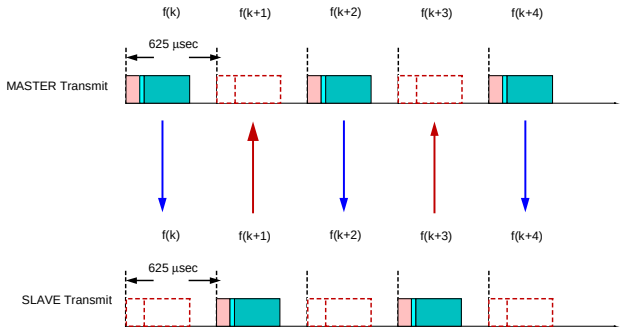
Access Codes

- **Channel Access Code (CAC):** Identifies a piconet, this code is used with all traffic exchanged on a piconet
- **Device Access Code (DAC):** Used for signaling, e.g. paging and response to paging
- **Inquiry Access Code (IAC):**
  - General Inquiry Access Code (GIAC)
    Common to all Bluetooth devices
  - Dedicated Inquiry Access Code (DIAC)
    Common to a class of Bluetooth devices
  - Inquiry process "finds" BT devices in range

Packet Header

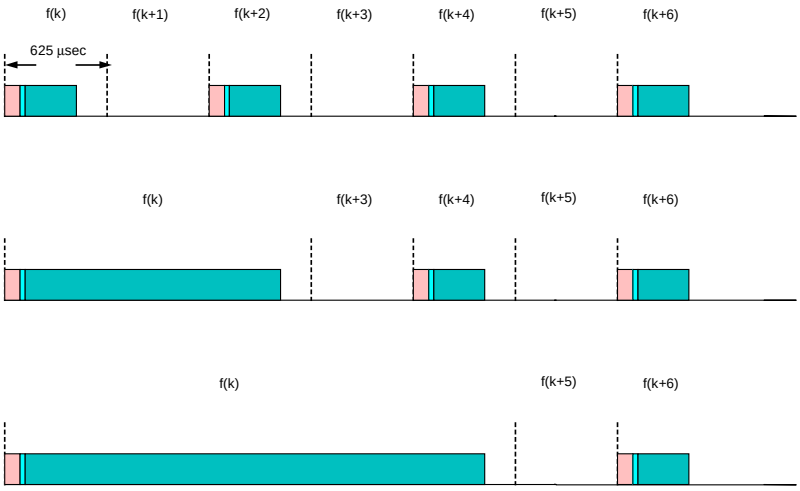
- **AM_ADDR:** 3 bit member address defines active members of a piconet
- **Data Type:** Defines various types of packets and their length. Allows non-addressed slaves to determine when they can transmit.
- **Flow Control**
- **Acknowledgement**: ACK/NAK field
- **HEC:** header error check, if an error is found, the entire packet is discarded

TDD and Packet Timing



- Bluetooth is time division duplex (TDD)
- About 220 µsec of the time slot is left for synthesizer settling
  Allows simple single loop synthesizers for frequency hop
- Master transmits in even number slots
  Slave transmits in odd number slots

Multi-slot Packets (Master Transmit)



Packet Types: System

- **ID:** Contains Device Access or Inquiry Access Code
  Used for paging, inquiry, and response
- **NULL**: Channel Access Code and Packet Header
  Used for acknowledgement and buffer flow control
- **POLL**: Similar to NULL packet but a slave response is required upon reception
- **FHS:** Contains Bluetooth device address and the clock information of sender, used in piconet set up and hop synchronization

High Quality Voice Packets

- **HV1 Packet**
  - 1/3 rate FEC protected, no retransmission, no CRC
  - 10 data bytes 1.25 msec of 64 kbps speech
  - Retransmitted every two time slots
- **HV2 Packet**
  - 2/3 rate FEC protected, no retransmission, no CRC
  - 20 data bytes 2.5 msec of 64 kbps speech
  - Retransmitted every 4 time slots
- **HV3 Packet**
  - No FEC, no retransmission, no CRC
  - 30 data bytes 3.75 msec of 64 kbps speech
  - Retransmitted every 6 time slots

Medium Rate Error Protected Data Packets

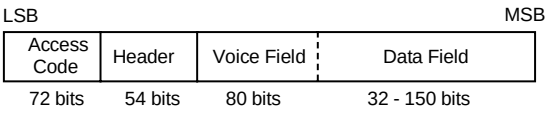
- **DM1: Data Medium rate**
  - 18 data bytes and occupies 1 time slot
  - 2/3 FEC plus 16 bit CRC
- **DM3**
  - 123 data bytes and occupies 3 time slots
  - 2/3 FEC plus 16 bit CRC
- **DM5**
  - 226 data bytes and occupied 5 time slots
  - 2/3 FEC plus 16 bit CRC

High Rate Data Packets No Error Protection

- **DH1: Data High rate**
  - 28 data bytes and occupies 1 time slot
  - 16 bit CRC, no FEC
- **DH3**
  - 185 data bytes and occupies 3 time slots
  - 16 bit CRC, no FEC
- **DH5**
  - 341 data bytes and occupied 5 time slots
  - 16 bit CRC, no FEC

Other Packets

- **DV:** Combined voice data packet,
  Transmitted as SCO packet
  - Voice: 80 bits No FEC and no retransmission
  - Data: up to 150 bits 2/3 FEC but retransmission permitted

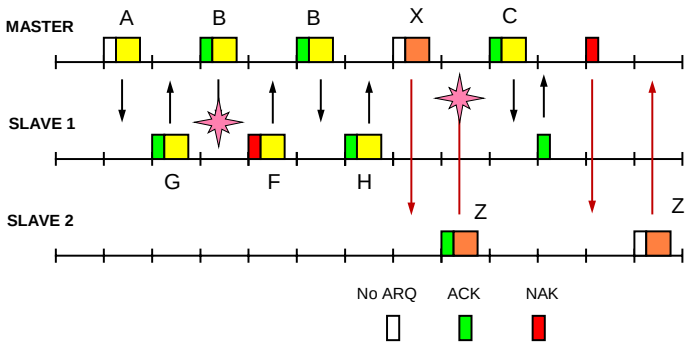


- **AUX1:** Similar to DH1 packet but 30 bytes, no CRC

Bluetooth Data Rates

Packet Type	Symmetric	Asymmetric	
DM1	108.8 kbps	108.8 kbps	108.8 kbps
DH1	172.8 kbps	172.8 kbps	172.8 kbps
DM3	258.1 kbps	172.8 kbps	172.8 kbps
DH3	390.4 kbps	585.6 kbps	86.4 kbps
DM5	286.7 kbps	477.8 kbps	36.3 kbps
DM5	433.9 kbps	723.2 kbps	57.6 kbps

Bluetooth ARQ



Physical Links

- **Bluetooth supports synchronous and asynchronous physical connections**
- **Asynchronous Connectionless (ACL) Link**
  - Master exchanges packets with any slave on a per slot basis
  - Packet switched connections to all active slaves in the piconet
  - Only a one ACL link per slave
  - ACL packets not addressed to a particular slave are broadcast packets and are read by all slaves

Physical Links

- **Synchronous Connection Oriented (SCO) Link**
  - Point to point synchronous symmetric link between the master and a particular slave
  - Circuit switched: time slots are reserved for time bounded information like voice
  - Master can support up to three SCO links with the same or different slaves
  - A slave can support up to three SCO links with one master or two with different masters
  - Link Manager (LM) establishes SCO link through LM protocol messages

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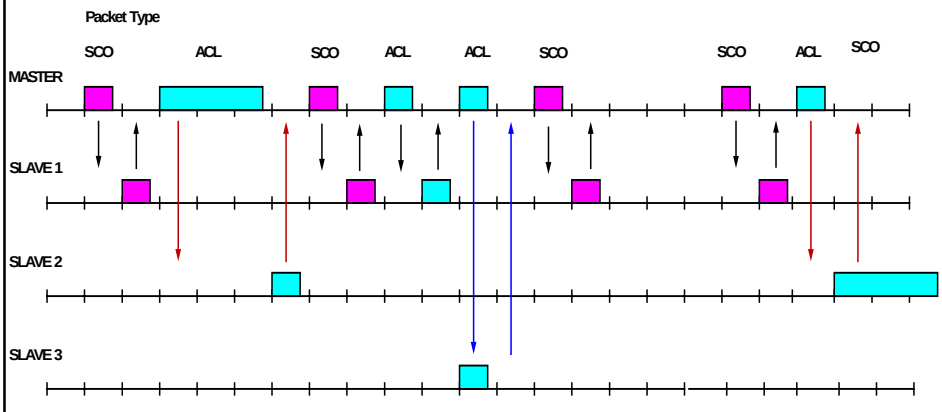
Multiple Links with Mixed Packets



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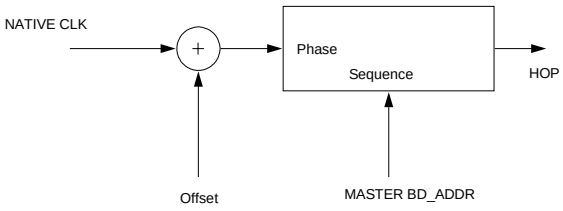
Bluetooth Addressing

- **Bluetooth Device Address (BD_ADDR)**
  - Uniquely identifies a Bluetooth device
  - 48 bit IEEE 802 address
- **Active Member Address (AM_ADDR)**
  - 3 bit address identifies active piconet slave
  - All zero address for broadcast
- **Parked Member Address (PM_ADDR)**
  - 8 bit address identifies an packed slave

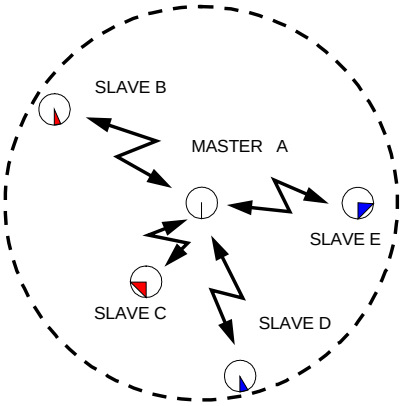
Synchronization



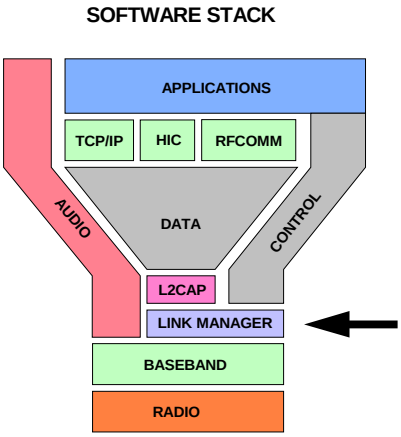
- Hopping sequence is established by the master device address, each Bluetooth device has a unique address
- Timing takes place in the Baseband layer
- Specification for NATIVE CLK is only ± 20 ppm

Clock Offsets Established

Each slave calculates an time offset from its local clock



Link Manager



Link Manager Protocol (LMP)

- **Link Configuration**
  - Supported features
  - Quality of Service, packet types
  - Security and Authentication
  - Establishes Logical Channels
    Beacon, Paging, Broadcast
- **Security Functions**
  - Authentication
  - Encryption and Key Management

Link Manager Protocol (LMP)

- **LMP runs between Link Mangers**
- **LMP sets up, terminates, and manages baseband connections**
- **LMP Functionality**
  - Attach and detach slaves
  - Control Master-Slave switch
    Used when a Slave/Master participates in another piconet as Master/Slave
  - Establish ACL and SCO links
  - Control low power modes: Park, Hold and Sniff

Bluetooth Connection States

Link Manager Controls BT operational modes

- **Active Mode**
  - BT can accommodate only 7 active slaves
  - AM_ADDR: 3 bit address given to each active slave
- **Hold Mode**
- **Park Mode**
- **Sniff Mode**

Hold Mode

- **ACL slave placed on Hold mode**
  - ACL packets no longer supported
  - SCO packets can still be exchanged
- **Frees Slave**
  - When master has no data, goes to low-power sleep
  - To attend another piconet
  - Scanning, inquiry, paging

    Slave finds or is found by another piconet
- **Slave keeps AM_ADDR**
- **Master assigns hold time**

  After hold time slave wakes up and synchronizes with traffic on the channel

Park Mode

- **Low activity, low power mode**
  - "Deeper Sleep" than Hold Mode
  - Devices wake up periodically to resynchronize and check for broadcast messages
- **Parked Device**
  - Gives up AM_ADDR
  - Remains synchronized
  - Receives:

    PM_ADDR: 8 bit Park Member Address

    AR_ADDR: 8 bit Access Request Address
- **Allows multiple slaves to be connected to a Master**

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Park Mode

- **Parked Member Address**

  Used in Master initiated reconnection
- **Access Request Address**

  Used in Slave initiated reconnection
- **Special all zero PM_ADDR**
  - Device must be unparked using 48 bit BM_ADDR
  - Allows almost an unlimited number of parked devices

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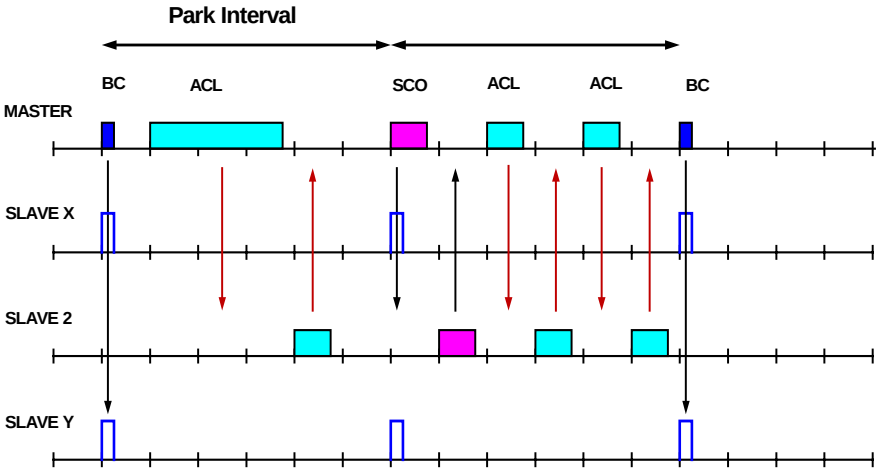
Park Mode Beacon Channel

- **Master establishes a Beacon Channel when a device is parked**
  - Maintains packed member synchronization
  - Communication via broadcast Link Manger messages

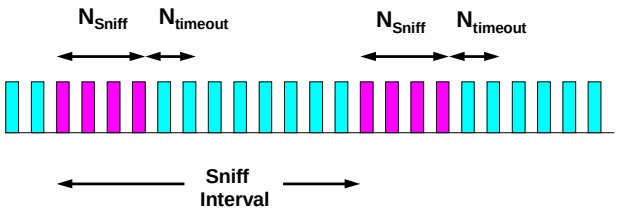
Park Mode



Sniff Mode

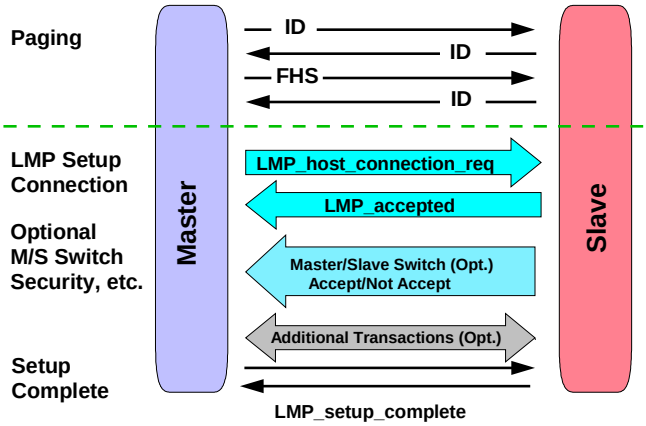
- **Sniff Mode much like Hold Mode**
  - Device remains active
  - Low power active mode
- **Slave retains AM_ADDR and goes to sleep**
  - Wakes up at assigned Sniff Interval to exchange packets

Sniff Mode



- Traffic reduced to periodic Sniff slots: Nsniff
- Slave listens for traffic with Slave AM_ADDR or Nsniff which ever is longer
- After traffic ceases, Slave continues to listen for Ntimeout
- LMP sets Sniff Mode parameters

ACL Link Setup Under LMP



Overview of LMP

Piconet Management

- ACL Link setup and detach
- SCO Link setup and detach
- Master/Slave Switch
- Low Power Modes
  - Hold
  - Sniff
  - Park

Link Configuration

- Power Control
- FEC Control
- QoS Control
- Link Timers
- Multi slot packet

Link Information

- LMP Version
- LMP supported features
- Clock and Timing

Bluetooth and Interference

Unlicensed Part 15 devices

- Must take interference from unlicensed/licensed services
- Must not give interference
- No interference protection

Bluetooth and Interference

Acknowledgement Scheme

- R&R: Rude and Robust
  - Robust: retransmits until message gets trough
  - Rude: keeps retransmitting, may negatively impact throughput of listen before transmit devices (IEE802.11)
- Frequency Hop will avoid some interference
- Will retransmitting lead to the Tragedy of the Commons with multiple devices in a Bluetooth enabled space?

Logical Link Control

- Logical Link Control and Adaptation Layer Protocol (L2CAP)
  - Layered over baseband protocol
  - Supports services
    - Protocol multiplexing
    - Segmentation/reassembly
    - Quality-of-Service (QoS)
    - Group abstractions

Protocol Multiplexing

- Baseband protocol treats all data packets equally
  - L2CAP needs to distinguish multiple protocols
    - Service Discovery Protocol
    - RFCOMM
    - Telephony Control

Segmentation/Reassembly

- Baseband packets are size-limited
  - Large packets need to be segmented by L2CAP into smaller baseband packets
  - Multiple baseband packets need to be reassembled into single, large packet
    - Integrity check performed on data
      - 16-bit CRC
      - Leverages ARQ mechanism used by baseband protocol

Quality-of-Service (QoS)

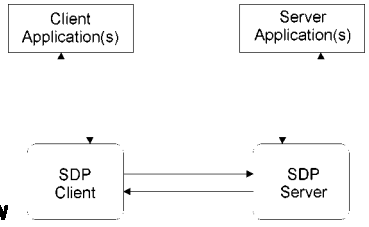
- L2CAP supports QoS message between Bluetooth devices
  - Only required to support “Best Effort” service
    - No guarantees
  - Other QoS services are optional
    - Token Rate
    - Token Bucket Size
    - Peak Bandwidth
    - Latency
    - Delay Variation

Group Abstraction

- Piconet supported by baseband protocol
  - Group Abstraction allows mapping of protocol groups to piconets
- Prevents higher-level protocols from needing to interact with baseband protocol or link manager

Service Discovery Protocol (SDP)

- Means for application to:
  - Discover services available on device
  - Determine characteristics of services available
- Single SDP server per device



- Device may contain both SDP Client and Server

SDP Requirements

- Ability to search services based on attribute
- Service discovery based on service class
- Allow browsing of services without apriori knowledge of service characteristics
- Allow for dynamic service discovery
  - Allows for device to enter or exit coverage area
- Uniquely-identified service/service classes

SDP Requirements

- Client on one device able to determine the services on another device without consulting a third device
- Simple enough for use by simple devices
- Allow for gradual service discovery
- Allow caching of service discovery

SDP Requirements

- Functions while using L2CAP as transport protocol
  - QoS info, segmentation, and protocol multiplexing
- Allows the usage of other service discovery protocols
- Support creation of new services without registration with central authority

SDP Basic Functionality

- SDP Client requests information from SDP Server
  - Information from Service Record returned
    - Contains list of Service Attributes
- Separate connection needs to be establish to initiate service
  - SDP connection used only to determine service availability

Sample Service Attributes

- ServiceName (human-readable)
- ServiceID (identifier for unique service instance)
- ServiceClassIDList (list of classes in which a service is an instance)
  - Example of color printer ServiceClassIDList
    - DuplexColorPostscriptPrintServiceClassID
    - ColorPostscriptPrinterServiceClassID
    - PostscriptPrinterServiceClassID
    - PrinterServiceClassID

SDP Wrap-up

- SDP allows the search and browsing of services available through nearby devices
- SDP allows an application to interface with the Bluetooth device to establish who is out there and what type of services are supported

RFCOMM

- Emulation of serial port over L2CAP protocol
  - Supports up to 60 simultaneous connections between two Bluetooth devices
    - Actual maximum of supported devices is implementation-specific
- Bluetooth acts as a replacement for the serial cable

Telephony Control Protocol

- Call Control
  - Establishment and release of speech or data calls between Bluetooth devices
- Group Management
  - Ease handling of groups of Bluetooth devices
- ConnectionLess
  - Exchange signaling information not related to on-going call

IrDA Interoperability

- Infrared Data Association (IrDA)
- Support development of applications that operate well over both short-range RF and IR
  - Achieve technology overlap with IrOBEX
    - Protocol defined by IrDA
    - Used also by Bluetooth
    - Mapped over RFCOMM and TCP/IP (optional)

Bluetooth IrOBEX (OBEX)

- Uses only connection-oriented OBEX
  - Mapped over connection-oriented Bluetooth architecture
- Enables exchange of data objects
- Simple commands
  - Connect, Disconnect, Put, Get, SetPath, Abort

WAP Interoperability

- Bluetooth used to communications between WAP client and server
  - Physical layer and link control
- In general, support communications between any two WAP-enabled Bluetooth devices

WAP Integration

- Provide ability for WAP applications to use Bluetooth device
  - Application-controlled communications
- Supported through PPP/RFCOMM
  - Also support SDP
- WDP Management Entity needed
  - Out-of-band mechanism for controlling protocol stack
    - Used to support detection of nodes and other events

First Commercial Bluetooth Product

- Hands free headset for cellular phone
- Introduced by Ericsson
  Fall 1999

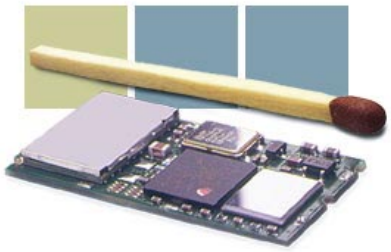
Getting Started in Bluetooth

- **Bluetooth technical specification is openly available**
  - www.bluetooth.com
  - Current news and hype!
- **Palo Pacific Technology**
  - www.palopt.com.au/bluetooth/devtools.html

Bluetooth Development Kits

- **Development Kits for Bluetooth**
  - Ericsson: www.ericsson.se
  - Digianswer
    - Danish, owned by Motorola
    - www.digianswer.com
  - Cambridge Silicon Radio
    - English
    - www.cambridgesiliconradio.com

Ericsson Radio Module



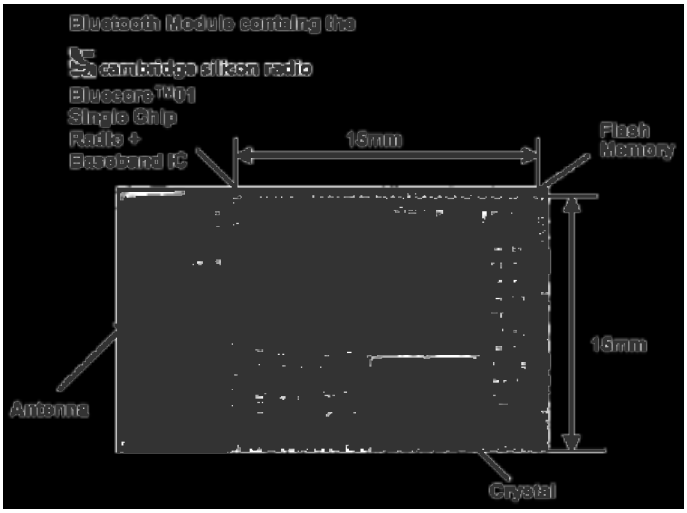
Operates as

- USB device
- UART

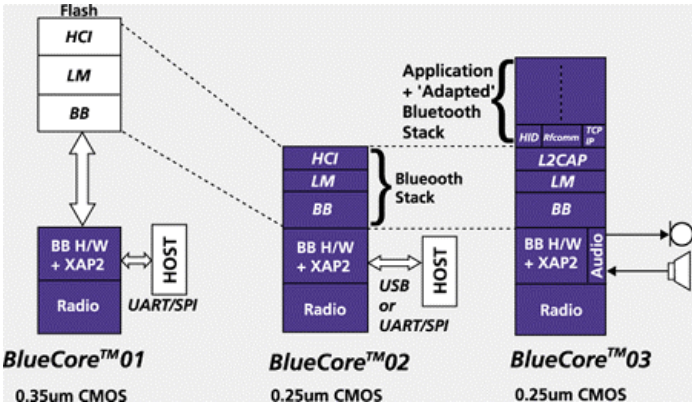
Ericsson Development Kit

- Starter kit available 1Q 2000
  $3000
- Full kit available

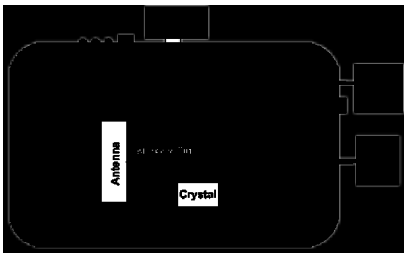
Cambridge Silicon Radio



CSR: BlueCore



CSR Development Kit



- Motherboard and software to interface with PC
- Contains BlueCore 01
- Cost: $8K
- Availability: now
- www.cambridgesiliconradio.com

Conclusion

- Bluetooth provides robust, short-range communications
- Flexible configuration can support multiple applications
  - Layers capable of supporting significant application variety growth
- Standard's loose implementation guidelines allow for introduction of new technology

Final Thoughts

- A single-chip solution is the ultimate goal
  - Around $5/chip
  - Several players have begun developing implementations
- Success of device depends on
  - The supplier's ability to deliver implementation at a low price point
  - Application development that is easily integrated with today's infrastructure
  - Ability of Bluetooth to meet market's expectations